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**OAK RIDGE FLYWHEEL EVALUATION LABORATORY
ANNUAL REPORT**

(October 1, 1979 - September 30, 1980)

R. S. Steele, Jr.
E. F. Babelay, Jr.
B. J. Sutton

April 1981

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UNION CARBIDE CORPORATION
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DEPARTMENT OF ENERGY**

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Y-12 Development Division

This work was conducted for and funded by the
Mechanical Energy Storage Technology Project
at Lawrence Livermore National Laboratory.

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ABSTRACT

The purpose of the Oak Ridge Flywheel Evaluation Laboratory Annual Report is to present work performed for and funded by the Mechanical Energy Storage Technology Project at Lawrence Livermore National Laboratory (LLNL). In addition to the management sections (schedules, budgets, and facility accomplishments), summaries are given for the ultimate speed evaluations of one flywheel built by Union Carbide Corporation, Nuclear Division (UCC-ND); four flywheels constructed under subcontracts from Sandia National Laboratory, Albuquerque; one fabricated by LLNL; and one manufactured by General Electric Company. Also included are the test results from two momentum transfer tests of the UCC-ND-designed flywheel. Prototype crash rings were used in a number of these tests, and a discussion of their performance is included.

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SUMMARY

The milestones for the Oak Ridge Flywheel Evaluation Laboratory (ORFEL) for FY 1980 included (1) passing a qualification review in January by a panel of experts assembled by the Lawrence Livermore National Laboratory (LLNL), and (2) evaluating by August 16, 1980, the ultimate speed capabilities of the four flywheel rotors built by William M. Brobeck and Associates, Garrett-AiResearch, Hercules Aerospace, and Rockwell-Rocketdyne. Both milestones were achieved. In addition to these four rotors, flywheels built by LLNL and General Electric were investigated as part of this series of tests; and their results are included in this report.

The results of these evaluations produced two composite flywheel records: (1) highest energy density (79.4 Wh/kg by Garrett-AiResearch's flywheel) and (2) most energy stored (1.94 kWh by Rockwell-Rocketdyne's flywheel). The series also demonstrated that the generic problem of attaching a heavy rim to a central shaft still lacks an optimum solution since all rim-type flywheels tested in ORFEL were limited by problems in this critical area.

Momentum transfer tests were performed as part of the qualification review process which emphasized the large torque values possible during a flywheel failure. Identical rim-type flywheels with stored energies of 0.19 and 0.14 kWh created average torque values at the base of their containments of 203 N·km (150,000 ft-lb) for 3.5 ms and 7 N·km (5,000 ft-lb) for 5 ms, respectively. These tests demonstrated not only the large torques possible, but the large variability in testing of this type.

Progress in the continuing task of maintaining a high-quality testing facility was demonstrated through the integration of capital equipment which increased crucial capabilities and improved quality assurance. The five such devices reported here include a computer system for data acquisition and control, a video system for real-time visual evaluation of a spinning flywheel, a structural dynamics analyzer for vibrational analysis, a moment-of-inertia measuring device to measure the actual polar moment of inertia, and a multichannel analog tape recorder to back up the real-time data acquisition systems and to allow a more comprehensive posttest signal analysis.

INTRODUCTION

The purpose of this report is to summarize the ORFEL program objectives, plans, and accomplishments for the FY 1980 budgetary period. The ORFEL is operated by Union Carbide Corporation, Nuclear Division (UCC-ND) as part of the Oak Ridge Y-12 Plant,^(a) Y-12 Development Division. The work reported herein was conducted for and funded by the Mechanical Energy Storage Technology (MEST) Project at LLNL.

This report presents only a brief summary of the test results and only the test measurements which bear directly on these results. Detailed test reports for each evaluation are now being written and will contain a more comprehensive presentation of the large quantity of data taken.

(a) Operated by the Union Carbide Corporation, Nuclear Division, for the Department of Energy.

TASK DESCRIPTION

PROGRAM OBJECTIVES AND FUNDING

The primary goals for the FY 1980 program were to pass a facility qualification review on January 31, 1980, and to complete an evaluation of the four rotor designs by William M. Brobeck and Associates, Garrett-AiResearch, Hercules Aerospace, and Rockwell-Rocketdyne Division that were developed and fabricated under various subcontracts from Sandia National Laboratory, Albuquerque (SNLA).

Other tasks to be completed as time and funds permitted were evaluations of flywheel designs by General Electric Company (GE), LLNL evaluation of prototype crash rings with these six flywheels, and the initiation of two proposals for facility upgrading capability tests.

The FY 1980 Activity Chart (figure 1) shows the original schedule with brackets and the actual schedule in braces. Although all activities were initiated later than anticipated, both of the milestones were accomplished on time.

Figure 1. ORFEL ACTIVITY SCHEDULE FOR FY 1980.

The spending schedule and funding levels for FY 1980 are shown in figure 2. Funding is received through SNLA/requests from the MEST Project at LLNL which are renewed each January. The funding increases in June and August were for (1) preliminary work regarding a facility move to a location more favorable for expansion and facility upgrading and (2) proposals for increasing facility capabilities. These two tasks were begun in FY 1980 but extended into FY 1981 and are not reported in this report.

Figure 2. ORFEL SPENDING SCHEDULE FOR FY 1980.

FACILITY QUALIFICATION REVIEW

On January 31, 1980, ORFEL and its principal investigator, R. S. Steele, were subjected to a qualification review by the Qualification Review Committee. The committee consisted of the following members:

- D. N. Frank - LLNL, nonvoting (Chairman)
- C. E. Bert - University of Oklahoma
- Roy Renner - Consultant to LLNL
- D. W. Rabenhorst - Applied Physics Laboratory
- R. L. Shaw - LLNL
- R. G. Stone - Consultant to LLNL

The following technical witnesses were also present:

- E. F. Babelay, Jr. - UCC-ND
- T. M. Barlow - LLNL
- W. H. Dodson - UCC-ND
- J. M. Googin - UCC-ND
- S. V. Kulkarni - LLNL
- E. Reimers - DOE, Washington

The committee's directive was to review and judge ORFEL's ability to perform valid flywheel tests. In performance of this duty, the committee was to review the test facility, review the test methods, deliberate on ORFEL's qualification, and recommend action.

The committee determined ORFEL to be qualified to perform flywheel testing. They further recommended that flywheel simulators be used prior to risking prototype rotors and that the safety restriction of 2 kWh maximum contained energy be reexamined.

Flywheel Simulators

Flywheel simulators are used at ORFEL to prove the validity of whirl maps developed for the suspension system. A whirl map is that mathematical model which predicts the frequency of asynchronous motion for a flywheel having particular physical properties, spinning at a particular speed. This need only be repeated when a prototype flywheel is to be tested which has a physical property (weight, polar, or diametrical moment of inertia) outside the boundaries of previous experience. The simulators used by ORFEL to test the boundaries are simple disks with arbor attachments approximating the ones used in the prototypes. Two simulators are required to define a boundary. Each has the same weight as the prototype, with one having the same polar moment of inertia and the other having the same ratio of polar-to-diametrical moment of inertia.

The boundaries were enlarged twice during this year, once for the Garrett flywheel and once for the Rockwell flywheel. The current whirl map has demonstrated validity within the boundaries listed in the following tabulation:

	<u>Minimum</u>	<u>Maximum</u>
Weight, kg	2.52	56.7
Polar Moment, $\text{kg}\cdot\text{m}^2$	0.01	22.5
Polar/Diametrical Ratio	2.00	1.56

There is no need to verify the stability of a prototype flywheel with a simulator if its properties fall within those listed, since stable regions are adequately defined on the map. Exceptions include special features of the prototype which may affect stability (arbor attachment, flexural resonance). In these cases, the cost versus benefit of simulators to model such features must be examined.

Safe Energy Storage Limit

The safe energy storage limit for the ORFEL facility of 2 kWh was reviewed by UCC-ND Energy Analysis personnel in response to the suggestion of the Qualification Review Committee. The engineering analysis, supported by the data generated in the torque tube test (performed as part of the qualification review) and other data found in the open literature, determined that a new safe energy storage limit of 4 kWh was acceptable.

Many questions remain regarding the safe containment of failing composite flywheels. Much more work must be done in this field before minimum adequate containment specifications can be derived.

ULTIMATE SPEED EVALUATION

UCCND-3

The first UCC-ND composite flywheel tested at ORFEL was designed and fabricated during the FY 1977 flywheel development program with the goal of optimizing energy density. That rim design was wound and cured in several stages and required several weeks to fabricate. The failure mode was expected to be radial delamination of the rim rather than a catastrophic hoop failure. The results of testing were given in the ORFEL FY 1979 Annual Report¹ and are included in the summary list of tests performed at ORFEL, as shown in table 1.

To accomplish sufficient testing to become qualified by January 1980, it was necessary for a flywheel to be fabricated in a shorter time period. Further, to fully demonstrate the instrumentation capability, a more aggressive failure mode was desired. By reducing the requirement for maximum energy density, a modified design was developed and fabricated. The anticipated failure mode for the modified design was hoop failure in the rim.

The resulting flywheel is shown in figure 3. The entire rim of this flywheel was wound and then cured. To reduce the possibility of radial delamination, Kevlar^(b) 29/epoxy was used on the inner portion and Kevlar 49/epoxy, with its higher modulus-to-density ratio, was used on the outer portion. The calculated stress distribution indicated that the first rim failure mode should be hoop failure at the interface between the two materials.

Flywheel UCCND-3 required 6.2 g for balance. Balance weights were lengths of 0.10-mm (0.004-in.)-thick by 25.4-mm (1.0-in.)-wide lead tape placed in two planes 54.10 mm (2.13 in.) apart. The weights had a mass component of $0.079 \text{ g}\cdot\text{m}^2$ located at 319° and a couple component of $0.064 \text{ g}\cdot\text{m}^2$ located in the 304° to 124° plane of the flywheel. The balanced runouts at 200 rps were 0.018 mm (0.0007 in.) at the top centerline and 0.036 mm (0.0014 in.) at the lower centerline of the flywheel.

During the first test for ultimate speed, the runout of the lower centerline of the hub increased with speed. Since the upper arbor runout remained fairly constant, a bending moment was placed on the tip of the shaft. Eventually, the dampers in the turbine exceeded their range; and excessive whirl developed. At 415 Hz, the arbor rubbed the arbor constraint. A decision was made to terminate the test run and inspect the flywheel. Visual inspection of the flywheel revealed that the bands had pulled from the outer surface of the rim. In addition to breaking the adhesive bond, some of the circumferential rim fibers were pulled from the surface in two locations. No other degradation of the flywheel was observed. In particular, no explanation for runout pattern was found. To assess the facility's ability to interpret a catastrophic failure, the flywheel was driven to failure without repair to the surface flaws and without regard to the excessive whirl. Catastrophic failure was

(b) E. I. du Pont de Nemours & Co., Inc.

Table 1
SUMMARY OF CRFEL-TESTED FLYWHEELS

Test	Flywheel Identification	Last Test	Designer	Material	Type	Diameter (m)	Height (m)	Polar Moment (kg·m ²)	Weight (kg)	Maximum Speed (rps)	Results
1	UCCND-2	9/79	UCC-ND	Kevlar 49	Bandwrap	0.508	0.100	0.501	11.15	450	0.56 kWh at 49.3 Wh/kg
2	UCCND-3	11/79	UCC-ND	Kevlar 49/29	Bandwrap	0.467	0.100	0.290	7.17	437	0.30 kWh at 42.2 Wh/kg
3	UCCND-4	12/79	UCC-ND	Kevlar 49/29	Bandwrap	0.467	0.100	0.290	7.17	349	203 N·km for 3.45 ms
4	UCCND-5	1/80	UCC-ND	Kevlar 49/29	Bandwrap	0.467	0.100	0.290	7.17	299	7 N·km for 5 ms
5	WMB-1	5/80	William M. Brobeck	Kevlar 49/S-glass	Biannulate rim	0.350	0.120	0.205	11.79	500	0.30 kWh at 25 Wh/kg
6	G-1	7/80	Garrett-AiResearch	Kevlar 49/29 S-glass graphite	Subcircular rim	0.584	0.110	1.050	15.55	463	1.23 kWh at 79.4 Wh/kg
7	H-1	8/80	Hercules Aerospace	Graphite	Prestressed disk	0.589	0.073	1.120	22.67	372	0.85 kWh at 37.5 Wh/kg
8	R-1	8/80	Rockwell-Rocketdyne	Graphite	Twin-disk hub	0.305	0.152	2.43	53.74	382	1.94 kWh at 36.1 Wh/kg
9	LLNL-1	10/80	LLNL	Graphite	Tapered disk	0.610	0.025	0.18	5.88	569	0.33 kWh at 56.12 Wh/kg
10	GE-1		General Electric	S-glass graphite	Disk with rim	0.450	0.036	0.237	10.08	Testing Incomplete

191390

Figure 3. FLYWHEEL UCCND-3 TESTED FOR ULTIMATE SPEED AT ORFEL.

encountered at 437 rps. Figure 4 shows the changing runout pattern with increasing speed. All points have been adjusted to zero runout at the 200-rps reference speed. This chart is practically identical to a similar display from the previous run. The change in relative position of the top and bottom of the arbor is obvious. The increase in outer radius of the flywheel with speed is seen in figure 5. A predicted radial growth curve for the rim alone is provided for comparison. Figure 6 shows time plots of four recorded signals at failure. The top trace is a 50% duty cycle square wave generated by a photocell observing a black strip painted over one-half the arbor's circumference. This signal is used as a phase and speed reference. The second is the trace of the runout sensor at the top centerline position. This trace indicates that the arbor was orbiting inside the arbor constraint just prior to the time of failure. The third and fourth traces are from the sensors monitoring the axial and radial location of the flywheel rim.

The major portion of the fibrous debris resulting from the wreck was material that had been used for the bands, since most of the rim remained intact. The turbine quill was only slightly bent and still held the arbor and flywheel hub securely attached to the turbine. The ultimate speed achieved was 437 rps. At that speed the flywheel was storing 0.303 kWh at 42.2 Wh/kg. Failure was caused by an overstress that was created in the spokes by the radial growth of the rim.

Figure 4. RUNOUT PLOTS FOR UCCND-3, RUN 15. (All runouts are translated to zero at 200 rps.)

Figure 5. RADIAL GROWTH MEASUREMENTS FOR UCCND-3, RUN 15.

Figure 6. FLYWHEEL PROXIMITY SENSOR SIGNALS IN THE TIME DOMAIN AT FAILURE, UCCND-3, RUN 15.

GARRETT-AIRESEARCH

The Garrett-AiResearch flywheel was the first tested of four flywheels that were built under SNLA subcontracts.² The high-energy density composite flywheel³ employed the same subcircular rim concept successfully used in their earlier flywheels. The primary new feature in this flywheel was the graphite composite hub which replaced the aluminum hub and significantly reduced the weight of total flywheel with only minor reduction in total energy storage. Thus, the energy density was significantly increased. Figure 7 shows the flywheel tested at ORFEL.

The flywheel achieved a maximum speed of 463 rps (27,780 rpm) and stored 1.23 kWh at 79.4 Wh/kg. Figure 8 is the runout plot for run 21 of the Garrett flywheel. Each line is the locus of vectors whose components are the magnitude and phase angle of the radial eccentricity of a surface on the flywheel. Data were taken at approximately 5-rps intervals in speed. The plot shows that between 430 and 450 rps the rims' eccentricities grew in

diametrically opposite directions. That is, the rims had grown away from the 0° and 180° spokes. This was the predicted failure mode for the flywheel, but it occurred at a speed slightly lower than the 504-rps (30,240-rpm) lift-off speed anticipated.

Runout of the hub grew rapidly at speeds above 450 rps. At 463 rps, the dynamic instability became excessive, and the test was terminated. During deceleration, the flywheel stabilized, then, again became unstable. The resulting instability grew until severe shaking caused the bond between the elastomer and the graphite hub to fail at 390 rps. The flywheel fell into the lip of a crash ring surrounding the wheel. The heat created by the subsequent rubbing caused the glow observed in the video record (figure 9). Failure was complete within approximately 20 s after the drop. Figure 10 shows the base of the quill adapter and the bond interface that failed.

WILLIAM M. BROBECK

The William M. Brobeck flywheel tested by ORFEL is shown in figure 11. The flywheel design⁴ featured a biannulated rim of S-2 Fiberglass^(c) and Kevlar-49 with an aluminum hub supported by a Kevlar-49 overwrap. The rim and hub were joined by tension-balanced spokes designed to expand with the rim.

This flywheel failed while maintaining a constant 500 rps (30,000 rpm). Total energy stored at that speed was 0.30 kWh at 25 Wh/kg. The phase reference is shown in figure 12 along with the runout traces for the various probes monitoring the flywheel during the 1 s prior to catastrophic failure. These traces show that an asynchronous movement was developing in the hub and arbor but not in the rim. Figure 13 is a plot of the runout of the inner surface of the hub at various speeds approximately 1/2 in. up from the bottom. These figures show that the hub became elliptical with increasing speed as the tension-balanced spokes pinched opposite sides of a diameter. The axis of the ellipse will be different at each spoke location, and these plots are valid only at the lower spoke level. It is noted that in the 500-rps pattern, which was recorded just prior to failure, the axis shifted approximately 45° . These data indicate that failure was the result of a vibratory motion of the hub in relation to the rim. The most likely cause was a slightly earlier failure in one or more of the spokes.

HERCULES AEROSPACE

The Hercules Aerospace flywheel was a circumferentially wrapped, graphite composite disk subsequently machined to a specific shape. A polysulfone matrix was used to allow residual stresses to be generated in the disk during a single-winding process. The flywheel is shown in figure 14.

(c) Owens-Corning Fiberglass Corp.

193634
Figure 7. GARRET-AIRESEARCH FLYWHEEL TESTED BY ORFEL.

Figure 8. RUNOUT PLOTS FOR THE FINAL TEST RUN OF THE GARRETT-AIRESEARCH FLYWHEEL.

195761
Figure 9. VIDEO RECORDING OF THE GARRETT-AIRESEARCH FLYWHEEL RUBBING THE CRASH RING DURING THE FINAL PORTION OF THE FAILURE.

195746
Figure 10. BASE OF THE QUILL ADAPTOR AT THE ELASTOMER-GRAPHITE INTERFACE.

Figure 11. WILLIAM M. BROBECK FLYWHEEL TESTED AT ORFEL.

194549

198274

Figure 12. TIME DOMAIN RUNOUT TRACES DURING THE FINAL 1 s OF RUN 13.

198275

Figure 13. RUNOUT PATTERN OF THE INNER SURFACE OF THE WILLIAM M. BROBECK FLYWHEEL'S HUB AT VARIOUS SPEEDS.

Testing of this flywheel was terminated during the fourth run at the maximum speed of 372 rps (22,320 rpm). Total energy stored was 0.85 kWh at 37.5 Wh/kg. The test was terminated by a pressure rise caused by material slung from the outer surface of the flywheel (figure 15). The flywheel was also experiencing circumferential cracking as seen by comparing the video pictures in figures 16 and 17.

In the design summary⁵ for this flywheel, it is noted that the transverse strength of the composite was not as good as originally expected. Thus, the circumferential cracking was the anticipated failure mode.

195697

Figure 14. HERCULES AEROSPACE FLYWHEEL TESTED BY ORFEL. THE OUTER AND BOTTOM SURFACES WERE PAINTED WHITE.

196019

Figure 15. GRAPHITE COMPOSITE SLINGS FROM THE OUTER SURFACE.

196611

Figure 16. VIDEO RECORDING OF THE LOWER FLYWHEEL SURFACE AT REST BEFORE FINAL RUN.

196610

Figure 17. VIDEO RECORDING OF THE LOWER FLYWHEEL SURFACE SPINNING AT 350 rev/s.

ROCKWELL-ROCKETDYNE

The Rockwell-Rocketdyne flywheel⁶ consisted of a graphite-composite rim wound upon a mandrel that remained with the flywheel as an aluminum liner for the rim. The rim was supported by upper and lower disks machined to a uniform stress distribution design. These disks were centered in the mandrel by 32 pins that were intended to maintain concentricity while the rim and mandrel grew away from the disks. Figure 18 is the Rockwell-Rocketdyne flywheel tested by ORFEL. The 56.7-kg (125-lb) flywheel was the heaviest flywheel yet tested by ORFEL.

The maximum speed achieved was 383 rps (22,980 rpm), 105% of the maximum design operating speed for the flywheel. Energy stored at this speed was 1.92 kWh at 36.1 Wh/kg. The maximum speed of the flywheel was limited by the fact that as speed increased, the pins were unable to keep the disks centered in the hub within the test facility limits. The runouts (twice the eccentricity) of the top disk and the bottom disk shown in figure 19, moved in opposite directions as the speed increased above 100 rps. At the maximum speed, the difference in these disk locations indicated a bending moment was being applied to the quill shaft above the safe allowable limit for the turbine. The fact that the runouts of the disks, measured near the bearing races, truly indicated eccentric movement of the disk relative to the rim was demonstrated in the final run in which the gap width between the lower disk and the rim at eight points around the circumference was measured using a video-metric technique. The verification is found in the close agreement between the video data and the regular sensor data shown in figure 20. The visible symptoms which terminated the test were a growing instability and the eventual "bottoming out" of a damper. This series of tests identified a characteristic failure mode for this flywheel. The actual speed at which a test of this flywheel design is terminated will be dependent upon the clearance and locational tolerance of the particular test

196051
Figure 18. ROCKWELL-ROCKETDYNE FLYWHEEL TESTED BY ORFEL. A PORTION OF THE OUTER SURFACE WAS PAINTED WHITE TO IMPROVE RADIAL PROXIMITY PROBE SENSITIVITY.

Figure 19. RUNOUT PLOTS FOR THE FINAL RUN.

unit and the ability of the test facility to tolerate either a growing quill-tip couple force, as in this test, or a growing mass imbalance, as would be the case for a double-bearing suspension system.

LAWRENCE LIVERMORE NATIONAL LABORATORY

Although the evaluation of the LLNL flywheel was concluded in FY 1981, it was begun in FY 1980 and is included in this report to group it with the remaining flywheels in this series. The flywheel shown in figure 21 was developed and fabricated by LLNL and given the local serial number LLNL-1.⁷ The flywheel material was a quasi-isotropic layer of uniaxial graphite fiber sheets machined to a modified Stodola-type taper. The flywheel was 610 mm (24 in.) in diameter and weighed 5.879 kg (12.9 lb). The maximum speed achieved was 569 rps. The energy stored was 0.326 kWh at 55.43 Wh/kg. Failure was sudden and catastrophic. The time-domain presentation of the sensor signals in figure 22 shows that all sensors were destroyed by flying debris within one revolution of the flywheel. These data and the runout plot in figure 23 both demonstrate that the flywheel was very stable up to the failure. An analysis of the flywheel run characteristics and the wreck debris indicates the failure to be a material failure.

GENERAL ELECTRIC COMPANY

The General Electric Flywheel⁸ evaluated at ORFEL had the local serial number GE-1. The flywheel shown in figure 24 was an S-glass, α -ply layup, quasi-isotropic, constant-thickness disk with a circumferentially wrapped graphite-composite ring. The aluminum hub was centrally bonded to the

Figure 20. RUNOUT PLOTS SHOWING GOOD AGREEMENT BETWEEN PROXIMITY SENSOR AND VIDEO DATA RUNOUT MEASUREMENTS OF THE LOWER DISK.

Figure 21. LLNL FLYWHEEL TESTED BY ORFEL.

196585

Synchronous Reference

Figure 22. TIME-DOMAIN PRESENTATION OF FLYWHEEL SENSOR SIGNALS NEAR THE TIME OF LLNL-1 FAILURE.

S-glass disk with an elastomeric bonding agent to accommodate the differential radial growth between the composite disk and the aluminum hub.

The maximum speed attained has been 535 rps. Energy stored at this speed was 0.371 kWh at 36 Wh/kg. Speed was not limited by the composite material but by whirl which was encountered near this speed. Although testing is incomplete, the whirl appears to be related to the strains placed upon the elastomeric bond. Confirmation must await further testing.

Figure 23. RUNOUT PLOT FOR RUN 7 OF FLYWHEEL LLNL-1.

196161
Figure 24. GENERAL ELECTRIC FLYWHEEL EVALUATED AT ORFEL.

MOMENTUM TRANSFER EVALUATION

TORQUE TUBE DEVELOPMENT

This task is directed toward gathering data on one of the two aspects of containment which must be considered in the design of a safe housing for flywheels. Those are the absorption of linear and angular momenta. Since most flywheel designs are expected to fail by shredding rather than breaking apart into chunks, containment requirements for resistance to penetration of these small fibers are not severe since each fiber has only a small amount of linear momentum which on the whole must add vectorially to zero. In fact, this is one of the very attractive features of composite flywheels.

On the other hand, the total angular momentum contained in a flywheel must be absorbed by the containment during a failure. The rate of absorption is proportional to the torque experienced by the containment support system. The key factor is how the failure mode of a flywheel interacts with the containment.

Since very little data exist upon which to base intelligent containment specifications, the composite flywheel development project at the Y-12 Plant began development of the testing apparatus required in FY 1977. Details of its construction are given in that project's annual report.⁹ The single deviation from that reported design was the addition of three 25.4-mm (1-in.) axial pins between the crash ring and housing floor to prevent ring rotation.

Figure 25 shows, schematically, how the torque tube and housing are located within the test chamber. Figure 26 is a photograph of the housing interior, while figure 27 shows a portion of the strain gauge installation on the torque tube itself.

A worst-case analysis presented in a previous report⁸ indicates a reasonable possibility of up to 271 N·km (200,000 ft·lb) applied to the torque tube. To calibrate to this level, a system for applying a static torque of this magnitude was fabricated. The system included a 12-in. I-beam bolted to the torque tube in place of the housing. Hydraulic rams, each capable of 20,000 lb, pushed each end of the 10-ft-long beam. Calibrated load cells monitored the ram force. The entire assembly is pictured in figure 28. An alternate configuration of the same equipment, shown in figure 29, was used to calibrate strain gauge response to lateral force along the 0° to 180° and 90° to 270° spin tank diameters. Actual torque achieved with the system was 184 N·km (136,000 ft·lb). The limiting factor was the increased extension requirements of the rams because of torsional slippage in bolt circles. The final calibration charts are presented in figures 30, 31, and 32.

FLYWHEEL UCCND-4 TEST RESULTS

Flywheel UCCND-4 was the first unit to demonstrate the ORFEL torque tube capability. In this test, the flywheel was accelerated inside the torque tube housing until failure occurred. The anticipated failure mode was the same spoke failure experienced in the two previous ultimate speed tests. During the failure, the torque tube twist and bending were recorded on

189859
Figure 25. SCHEMATIC DRAWING OF TORQUE TUBE AND CONTAINMENT HOUSING IN THE ORFEL TEST CHAMBER.

193287
Figure 26. TORQUE TUBE HOUSING.

191801
Figure 27. TORQUE TUBE STRAIN GAGING.

192042
Figure 28. ASSEMBLY USED TO STATICALLY CALIBRATE TORQUE TUBE.

192043
Figure 29. ASSEMBLY CONFIGURATION FOR LATERAL LOAD CALIBRATION.

192575
Figure 30. CALIBRATION CHART FOR TORQUE.

192580
Figure 31. CALIBRATION CHART FOR LATERAL LEAD IN THE 0°-180° PLANE.

192583
Figure 32. CALIBRATION CHART FOR LATERAL LOAD IN THE 90°-270° PLANE.

a multichannel FM tape recorder at an 80-kHz bandwidth. Posttest data reduction produced the torque history of the test.

Flywheel UCCND-4 was fabricated according to the modified UCC-ND design and appeared identical to UCCND-3 in figure 3. In this particular flywheel, however, higher modulus Kevlar 49 was substituted for Kevlar 29 as the spoke fiber in an attempt to reduce spoke separation from the outside contour of the rim. A blue dye was added to the spoke matrix to help identify spoke material in the debris. Unfortunately, an inadequate amount of dye was used and there was an insignificant color change.

An acceptable balance required 14.90 g. Weight application technique was the same as that in previous tests. The mass weight $0.617 \text{ g}\cdot\text{m}$ was at 67° . Couple balance required weights of $0.060 \text{ g}\cdot\text{m}^2$ at 203° on the top balance plane and 23° on the bottom balance plane. These weights brought the arbor top runout to 0.009 mm (0.0004 in.) at 173° and the arbor bottom to 0.070 mm (0.003 in.) at 24° at a speed of 300 rps.

During the run, the test chamber was configured as shown earlier in figure 25. Chamber pressure was less than $0.2 \mu\text{m}$ throughout the test. Flywheel instrumentation was limited to a single runout probe at the top of the arbor and square wave for phase reference. A total of four strain bridge outputs were recorded. Two recorded the lateral bending along the 0° and 90° planes and two formed a set of redundant torque bridges. Two additional signals, the turbine tachometer and the signal from an accelerometer mounted on the test chamber lid were also recorded.

This latter set shows that runout stability was excellent until a sudden increase occurred approximately 100 ms prior to the first large spike seen in the accelerometer signal from the chamber lid. The speed is shown to be constant until this time and then begins to slow.

A plausible scenario is that one or more spokes began to fracture at T-100 ms. Others followed until at T = 0 a significant portion of spoke material left the flywheel, causing the increasingly unstable flywheel to overload any remaining spokes.

Figure 33 shows the signals from one of the torque tube strain bridges. As indicated, the peak torque is $515 \text{ N}\cdot\text{km}$ (380,000 ft-lb) with an average of approximately $203 \text{ N}\cdot\text{km}$ (150,000 ft-lb) over the 3.45-ms pulse period. Assuming certain characteristics outlined in the Appendix, the energy under this torque curve was calculated to be approximately 0.17 kWh or approximately 90% of the total energy stored in the flywheel.

The actual failure mode and reason for the large torque value became obvious in the photographs of the debris. Figure 34 shows how a wedge, mostly of spoke material, grew until the flywheel jammed between the wedge and the opposite side of the chamber. In figure 35 the underside of the housing lid is shown revealing the depolymerized resin directly above the wedge. Figure 36 shows the pattern in the bottom of the housing. Finally, figure 37 shows the flywheel separate from the housing.

198453
Figure 33. TORQUE TUBE SIGNAL GENERATED DURING FAILURE OF UCCND-4.

192209
Figure 35. INSIDE OF THE HOUSING LID WITH DEPOLYMERIZED RESIN DIRECTLY ABOVE THE WEDGE.

192325
Figure 36. PATTERN LIFE IN THE BOTTOM OF THE CONTAINMENT HOUSING BY BRAKING FLYWHEEL.

192210
Figure 34. FLYWHEEL UCCND-4 IN TORQUE TUBE AFTER FAILURE.

192330
Figure 37. DETAIL OF FLYWHEEL AND WEDGE REMOVED FROM CONTAINMENT HOUSING.

FLYWHEEL UCCND-5 TEST RESULTS

The failure characteristics of high-speed, nonhomogeneous objects are usually subject to wide variation. To gain knowledge of the scatter in these data, a second momentum transfer test was performed in which the test parameters were kept as close as possible to those of the first test. Thus, UCCND-5 was identical to UCCND-4, and the same test configurations were used for both tests.

The major measurable difference between the two flywheels was the balance required. Flywheel UCCND-5 required a total of 27 g of weights in three locations. The mass weight was 0.632 g·m at 99°. Couple balance required 0.152 g·m² at 187° on the top plane and 7° on the bottom plane. These weights reduced the runouts to 0.013 mm (0.0005 in.) on the top plane and 0.002 mm (0.0001 in.) on the bottom plane at 300 rps.

Flywheel UCCND-5 failed at 299 rps. The waveform of the torque shown in figure 38 is nearly identical to the previous test but has a longer pulse length (5 ms) and lower peak amplitude (16,000 ft-lb) and lower average amplitude (5,000 ft-lb). These lower amplitudes are primarily due to the fact that this pulse form did not occur until 400 ms after failure initiated. Thus, considerable energy was dissipated prior to the buildup of the wedge. Figure 39 shows the flywheel rim jammed in the torque tube housing.

CONTAINMENT RING EVALUATION

Several containment rings were designed and fabricated by the General Electric Co., Space Division, under a subcontract from LLNL, for evaluation with the flywheels that were tested this fiscal year. Only containment rings for the Garrett-AiResearch, Hercules Aerospace, Rockwell-Rocketdyne, LLNL, and GE flywheels were included in the tests. Of these, only the Hercules, Garrett-AiResearch, and the LLNL flywheels failed when a containment ring was installed; and only the latter two failed catastrophically. Further—since the tests were, primarily, flywheel evaluations—some compromises were made which reduced the rings' performances. First, the rings were not mounted as securely as they would be in an automotive application. Second, two diametrically opposed, 1-in.-diameter holes (required for runout sensor placements) weakened the rings considerably. Despite these drawbacks, several observations were made.

The containment rings with Kevlar cloth overwraps trapped significant amounts of air and moisture. Consequences were an inability to reach the low testing pressure desired (1 μ m) in the spin chamber within a reasonable time period and loosening of the cloth overwrap as the bulk of the moisture evaporated.

The failures of the Hercules and Garrett flywheels demonstrated the effect of attack angle upon penetration characteristics. The test and configurations, figure 40, were similar. Small parts of the graphite spokes from the Garrett flywheel penetrated the aluminum ring some time fairly late in the wreck as seen in figure 41. These spoke fibers were radially oriented and had a nearly perpendicular attack angle. The Hercules flywheel slung graphite fibers of roughly the same size, but the fibers were circumferentially oriented. Note in figure 42 that the only damage to this containment ring is scratches in the paint.

Figure 38. WAVEFORM DURING TORQUE PULSE, RESULTING FROM FAILURE OF UCCND-5 AT 10,000 ft-lb/V.

192905

Figure 39. THE UCCND-5 FLYWHEEL RIM FRAGMENT IN TORQUE TUBE HOUSING.

195305
 Figure 40. HERCULES FLYWHEEL AND PROTOTYPE CONTAINMENT RING IN TYPICAL TEST CONFIGURATION.

195752
 Figure 41. HOLES PUNCTURED IN ALUMINUM CONTAINMENT RING BY GRAPHITE SPOKE MATERIAL FROM GARRETT-AIRESEARCH FLYWHEEL.

196022
 Figure 42. SCRATCHES CAUSED BY GRAPHITE FIBERS SLUNG FROM PERIMETER OF HERCULES FLYWHEEL.

The only containment ring to experience an in-plane burst was the one surrounding the LLNL quasi-isotropic tapered disk. This containment ring, shown in figure 43, appears to have been loaded with uniform internal pressure until it ruptured, almost simultaneously, at both portholes. There is little indication of how this ring would have responded had the portholes not been required.

Figure 43. FAILED CONTAINMENT RING FOR LLNL 1.

197029

FACILITY CAPABILITY IMPROVEMENTS

During FY 1980, the ORFEL facility continued to improve both the quality and quantity of data necessary for comprehensive flywheel evaluation through the addition of several capital equipment items. Five particularly significant items are briefly described in this section.

Real-time data acquisition and manipulation is greatly improved with the addition of a laboratory computer system. In addition, the system records many times the amount of data than was previously possible. The computer has standardized data format and, thus, increased quality assurance and eased data interpretation. The typical test-run printout seen in figure 44 gives the test title for labeling and referencing, calibration and location of each proximity sensor, balance weights and location, and the runout observed by each sensor adjusted for the sensor phase location at selected speeds and time intervals. These runout data are plotted in real time on a storage oscilloscope and are later used to produce the runout plots presented earlier in this report. The computer-test interaction will continually be improved as it is programmed to assume duties ranging from alarm sensing and reaction to video title preparation.

Real-time visual monitoring of the flywheel during a test is now possible through the use of a low-light, high-resolution video system. The flywheel motion can be "frozen" by using a 1- μ s-pulse-duration strobe light synchronized with the flywheel. The standard video framing rate of 30 frames/s does not allow detailed analysis of rapid failures. Instead, the system is designed to provide information regarding run characteristics prior to failure. Examples of this are the circumferential cracking of the Hercules flywheel in figure 17 and the overwrap failures of the flywheel by Brobeck (WMB-1) seen in figure 45. An example of the image quality that is possible is seen in the close-up of the 0.7-mm gap between the hub disk and rim of the Rockwell flywheel shown in figure 46. In this frame, the flywheel was rotating at 320 rps with a surface velocity of 402 m/s; and the strobe light was synchronous with the 90° location of the flywheel.

The ability to analyze flywheel motions of a periodic nature was achieved with the addition of a structural dynamics analyzer. This is an essentially dual-channel frequency analyzer capable of displaying signals in both frequency and time domains. The digital analyzer is also supported by software which allows the device to perform experimental modal analyses on structures such as flywheels. The frequency-domain analysis capability is crucial in analyzing the whirl phenomena which must always be considered in flywheel testing. Figure 47 shows a typical time-domain display of a runout signal with a synchronous and a whirl component. The ability to determine the shape of a particular flexural resonant mode of a flywheel is crucial in the interpretation of proximity sensor data when flexural vibration of the flywheel is present. The modal shape at a particular resonant frequency of the LLNL flywheel is shown in figure 48.

The polar moment of inertia is the property which allows the flywheel to store kinetic energy. Until recently, its calculated value was relied upon; however, it is often difficult to

LLNL1 20-OCT-80 RUN NUMBER 7
FILE NAME IS LLNL7

PROBE (NAME)	CALIBRATION FACTOR (MILS/VOLT)	INITIAL STANDOFF (VOLTS)	ANGULAR LOCATION (DEG.)	ORIENTATION (DESCRIPTION)
A	10.00	6.45	0.00	ARBOR TOP
B	10.00	3.19	310.00	BOTTOM BUTTON
C	10.00	4.69	0.00	RIM AXIAL
D	10.00	2.21	5.00	RIM RADIAL

BALANCE WEIGHTS
MASS(GRAMS) LOCATION(DEG.)

SPEED DATA SAMPLE INTERVAL(REV/SEC) 5
TIME DATA SAMPLE INTERVAL(SEC.) 60
FULL SCALE FOR PLOT(MILS) 25

I	SPEED HZ / RPM	ELAPSE TIME HOUR:MIN:SEC.	PROBE A		PROBE B		PROBE C		PROBE D		PROBE	
			R MILS G(I,3)	ANGLE DEG. G(I,4)	R MILS G(I,5)	ANGLE DEG. G(I,6)	R MILS G(I,7)	ANGLE DEG. G(I,8)	R MILS G(I,9)	ANGLE DEG. G(I,10)	R MILS G(I,11)	ANGLE DEG. G(I,12)
1	102.13/ 6128	0: 0: 0	39.807	334.004	34.720	75.014	91.845	226.477	102.573	171.648		
2	102.31/ 6139	0: 0: 3	40.981	350.049	35.262	92.258	95.958	245.257	101.387	181.682		
3	102.13/ 6128	0: 0: 5	40.793	1.379	35.003	104.692	96.129	258.652	97.523	189.549		
4	102.49/ 6149	0: 0: 7	39.821	12.027	34.577	116.450	93.197	271.075	93.026	195.940		
5	102.13/ 6128	0: 0: 9	38.601	21.368	33.928	126.916	89.775	282.195	87.622	201.525		
6	102.49/ 6149	0: 0: 11	37.189	29.298	32.912	135.967	85.150	292.157	81.193	207.032		
7	80.79/ 4848	0: 0: 13	35.461	36.207	31.474	144.033	80.291	300.802	76.126	209.618		
8	38.96/ 2338	0: 0: 15	32.926	44.551	28.844	154.590	72.817	311.147	72.211	210.190		
9	40.98/ 2459	0: 0: 17	31.055	49.830	27.076	161.178	67.227	317.965	70.636	209.899		
10	42.32/ 2539	0: 0: 19	29.204	54.125	25.339	166.898	61.811	323.465	71.984	208.613		
11	43.31/ 2599	0: 0: 21	27.410	57.491	23.593	171.510	56.966	327.850	73.680	207.802		
12	44.81/ 2688	0: 0: 23	25.674	60.059	21.990	175.377	52.578	330.990	76.408	207.421		
13	46.63/ 2798	0: 0: 25	24.134	61.861	20.564	178.186	48.885	333.409	78.835	207.735		
14	46.99/ 2819	0: 0: 27	22.768	63.347	19.299	181.006	45.934	335.204	80.660	208.369		
15	50.15/ 3009	0: 0: 30	20.757	65.127	17.334	184.338	41.374	337.405	83.677	209.835		
16	55.47/ 3328	0: 0: 38	17.465	67.328	14.159	190.111	34.587	340.232	87.859	214.496		
17	61.15/ 3669	0: 0: 45	15.654	68.327	12.394	193.636	31.129	341.363	89.759	218.261		
18	65.64/ 3938	0: 0: 53	14.250	69.319	11.083	196.714	28.523	342.245	91.008	221.960		
19	70.30/ 4218	0: 0: 58	13.559	69.877	10.501	198.429	27.360	342.532	91.491	224.173		
20	75.49/ 4529	0: 1: 7	12.660	70.473	9.703	200.718	26.001	343.122	91.753	227.506		
21	80.85/ 4839	0: 1: 14	12.035	70.774	9.240	202.744	25.089	343.566	92.054	230.027		
22	85.48/ 5129	0: 1: 22	11.526	71.012	8.740	204.356	24.346	343.828	92.535	232.161		
23	90.80/ 5448	0: 1: 29	11.154	71.266	8.409	205.677	23.738	343.824	93.131	233.942		
24	95.31/ 5719	0: 1: 35	10.860	71.220	8.150	206.645	23.546	344.110	93.276	235.476		
25	100.98/ 6059	0: 1: 44	10.613	71.232	7.879	207.891	23.226	344.652	93.423	237.101		
26	100.65/ 6039	0: 2: 43	10.465	71.049	7.661	207.925	22.821	343.808	93.727	237.073		
27	101.14/ 6068	0: 3: 43	10.387	71.188	7.530	208.320	23.067	344.069	93.655	237.245		
28	100.33/ 6020	0: 4: 44	10.351	71.223	7.503	208.506	22.662	343.386	93.913	237.143		
29	105.79/ 6348	0: 5: 8	10.196	71.140	7.294	208.726	22.596	344.256	94.112	238.553		
30	110.65/ 6639	0: 5: 16	10.006	71.064	7.082	209.778	22.114	344.399	94.480	239.909		
31	115.15/ 6909	0: 5: 22	9.895	71.142	7.038	210.367	22.027	344.063	94.731	241.110		
32	120.48/ 7229	0: 5: 30	9.770	71.194	6.837	210.504	22.051	344.665	95.051	242.735		
33	125.65/ 7539	0: 5: 39	9.655	71.299	6.779	211.087	21.826	345.679	95.213	244.155		
34	130.81/ 7849	0: 5: 47	9.594	71.175	6.671	211.211	21.429	346.059	95.578	245.090		
35	136.31/ 8179	0: 5: 53	9.506	71.202	6.618	212.140	21.182	345.938	95.620	246.506		
36	140.80/ 8448	0: 6: 1	9.440	71.378	6.510	212.136	21.284	345.772	95.977	247.164		
37	145.30/ 8718	0: 6: 7	9.403	71.408	6.510	212.136	21.283	346.921	96.045	247.760		
38	150.15/ 9009	0: 6: 16	9.331	71.470	6.449	212.416	20.813	347.430	96.280	248.746		
39	155.14/ 9309	0: 6: 23	9.280	71.470	6.382	212.854	20.849	346.792	96.559	249.463		
40	160.82/ 9649	0: 6: 30	9.243	71.511	6.341	213.077	21.060	347.530	96.766	250.182		
41	165.48/ 9929	0: 6: 38	9.177	71.372	6.311	213.458	20.872	348.680	97.019	250.862		
42	171.48/ 10289	0: 6: 47	9.166	71.584	6.277	213.365	20.741	348.135	97.360	251.528		
43	175.15/ 10509	0: 6: 55	9.151	71.543	6.224	213.375	20.966	349.244	97.436	252.243		
44	181.15/ 10869	0: 7: 3	9.094	71.649	6.219	213.519	20.618	349.383	97.829	252.606		
45	185.99/ 11159	0: 7: 10	9.058	71.682	6.161	213.202	20.726	349.022	98.604	253.279		
46	190.80/ 11448	0: 7: 19	9.006	71.683	6.163	213.680	20.942	349.834	98.352	253.754		
47	195.15/ 11709	0: 7: 27	8.960	71.476	6.180	214.214	20.904	349.670	98.726	254.161		
48	200.33/ 12020	0: 7: 44	8.960	71.476	6.185	214.055	21.023	350.980	98.809	254.642		
49	199.98/ 11999	0: 8: 43	8.960	71.476	6.144	214.292	21.229	351.246	98.875	254.700		
50	205.65/ 12339	0: 9: 34	8.914	71.377	6.124	214.412	21.011	350.372	99.393	255.222		

Figure 44. TYPICAL COMPUTER PRINTOUT FROM ORFEL TEST.

194890

Figure 45. VIDEO RECORDING OF OVERWRAP FAILURES IN FLYWHEEL WMB-1.

197670

Figure 46. VIDEO PHOTOGRAPH OF THE 0.7 mm GAP BETWEEN THE DISK AND THE RIM OF THE ROCKWELL FLYWHEEL AT 320 rps.

Figure 47. TYPICAL TIME AND FREQUENCY DOMAIN OF A RUNOUT SENSOR'S RESPONSE TO BOTH SYNCHRONOUS RUNOUT AND WHIRL.

Figure 48. MODE SHAPE FOR FLEXURAL VIBRATION OF THE LLNL FLYWHEEL AT 444 Hz.

calculate and is sensitive to the physical properties which are assumed to exist in the flywheel. This year, ORFEL has added a moment-of-inertia measuring device for use with flywheels weighing up to 90 kg (200 lb). This will allow the use of a measured value and, thus, increase the confidence in the quality of the data reported by ORFEL.

Finally, since all real-time data acquisition is subject to intermittent operator errors and equipment failures, a 14-channel FM analog tape recorder has been added to the test facility as a backup recording device. The analog tape recorder is one of the most reliable recording techniques available. It is used in ORFEL to record the raw signals from the runout sensors, pressure and speed indicators, and room noise for up to 1 h with a 10-kHz bandwidth before rewinding or changing the tape. Much longer times are possible with reduced bandwidths. The recorder can be controlled by the computer and, consequently, can be continuously run in fatigue tests with instructions to record over previous data.

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APPENDIX

ESTIMATE OF ENERGY ABSORBED BY TORQUE TUBE

Containment requirements for composite flywheels are generally thought to be rather mild because of the presumption that most of the energy stored in the flywheel is converted to heat during the shredding of the composite during failure. The test of UCCND-4 caused little damage to the flywheel rim or hub. The only significant signs of high temperature are associated with the wedge of spoke debris.

An estimate of the amount of energy stored in the flywheel that was absorbed by the torque tube is found in the following manner. First, the torque pulse, shown in figure 25 is modeled as shown in figure A-1.

Figure A-1. MODEL OF TORQUE PULSE FROM UCCND-4.

The average torque for the entire pulse is found by determining the weighted average of the triangular and rectangular components:

$$\begin{aligned}
 T_{ave} &= \left\{ \frac{1}{3} (284 \times 10^3 \text{ ft-lb}) (2.45 \text{ ms}) + 284 \times 10^3 \text{ ft-lb} \right. \\
 &\quad \left. (1.0 \text{ ms}) \right\} / 3.45 \text{ ms} \\
 &= 1.495 \times 10^5 \text{ ft-lb}
 \end{aligned} \tag{1}$$

where T_{ave} is the average torque over the 3.45-ms pulse.

The deceleration rate of the rim of the flywheel is determined by assuming a constant average torque and using the polar moment of inertia of the flywheel rim:

$$\begin{aligned}
 \ddot{\Theta} &= T_{ave} / I \\
 &= (1.495 \times 10^5 \text{ ft-lb}) / 2.389 \text{ in.-lb-s}^2 \\
 &= 7.509 \times 10^5 \text{ rad/s}^2
 \end{aligned} \tag{2}$$

where $\ddot{\Theta}$ is the angular deceleration and I is the polar moment of inertia.

By integrating twice and using the boundary condition of angular velocity ($\dot{\Theta}$) equal to 2,193 rad/s at time equal zero and the initial angle (Θ) of zero at time equal zero, the following relation/angular orientation as a function of time is derived:

$$\Theta(t) = -3.755 \times 10^5 t^2 + 2.193 \times 10^3 t. \tag{3}$$

Total angle of rotation in 3.45 ms is:

$$\Theta (3.45 \text{ ms}) = 3.046 \text{ rad.} \quad (4)$$

The total work done (energy used) in stopping the rim was:

$$\begin{aligned} \text{Work} &= T\Theta \\ &= (1.495 \times 10^5 \text{ ft-lb}) (3.096 \text{ rad}) / (2.656 \times 10^6 \text{ ft-lb/kWh}) \\ &= 0.174 \text{ kWh} \end{aligned} \quad (5)$$

The total energy stored in the flywheel was 0.193 kWh.

Thus, approximately 90% of the total flywheel energy was transferred to the containment and its support system.

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Babelay, E. F., Jr. (5)
 Bernander, N. K.
 Casstevens, J. M.
 Dodson, W. H./Googin, J. M.
 Fee, G. G.
 Ferguson, J. E.
 Gray, J. R.
 Jones, F. W.
 Kahl, K. G.
 Keith, A.
 Kite, H. T.
 Koger, J. W.
 Mills, J. M., Jr.
 Post, D. W.
 Robinette, B. K.
 Steele, R. S. (15)
 Stoner, H. H./Butturini, W. G./Dritt, W. S.
 Tewes, W. E.
 Thompson, W. F.
 Tillson, F. V.
 Tunnell, H. A.
 Vanstrum, P. R.
 White, B. J.
 Y-12 Central Files (master copy)
 Y-12 Central Files (route copy)
 Y-12 Central Files (Y-12RC)
 Y 12 Control Files (5)

Owens Corning Fiberglas - Granville

Kay, J. F.
 Loud, S. N.

Paducah Gaseous Diffusion Plant

Bewley, H. D.

Picatinny Arsenal Library - Dover

Anzolone, A. M.

Public Service Electric and Gas Company - Newark, N. J.

Schneider, T. R.

Rockwell International - Canoga Park

Davis, D. E.
 Ginsberg, B. R.

Rockwell International - Downey

Notti, J. E.

Sandia National Laboratories - Albuquerque

Gerstle, F. P.
 Miller, A. K.
 Reedy, E. D., Jr.
 Reuter, R. C.
 Woods, R.

Sandia National Laboratories - Livermore

Hargreave, R. M.
 Spencer, W. J.

Tennessee Valley Authority

Siegel, G. R. (2)

Test Devices, Inc. - Stow, Mass.

Sonnichsen, E. H.

Union Carbide Corporation - New York

Tindley, S. W.

University of Wisconsin - Madison

Frank, A. A.

U.S. Army - Fort Belvoir

Amstutz, L. I. (USAMERADCOM)

U.S. Flywheel, Incorporated - San Juan, Calif.

Swartout, B. E.